The Inert Doublet Model
...as the Dark Matter

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Outline

The Inert doublet model (IDM)

- Motivation
- The Theory
- Its Dark Matter Phenomenology

Motivation:

The Inert Doublet Model (IDM) can provide a:

- Dark Matter particle [Ma ’06; Barbieri ‘06; Honorez *et al.* ’07, *M.G. et al.* ’07]
- Heavy SM Higgs to alleviate the ‘LEP paradox’ [Barbieri *et al. ’06*]
- radiative Electroweak Symmetry Breaking [Hambye & Tytgat ‘07]
- way to generate Small Neutrino Masses [Ma ‘06]
- ....

... and it is a very minimal extension of the SM

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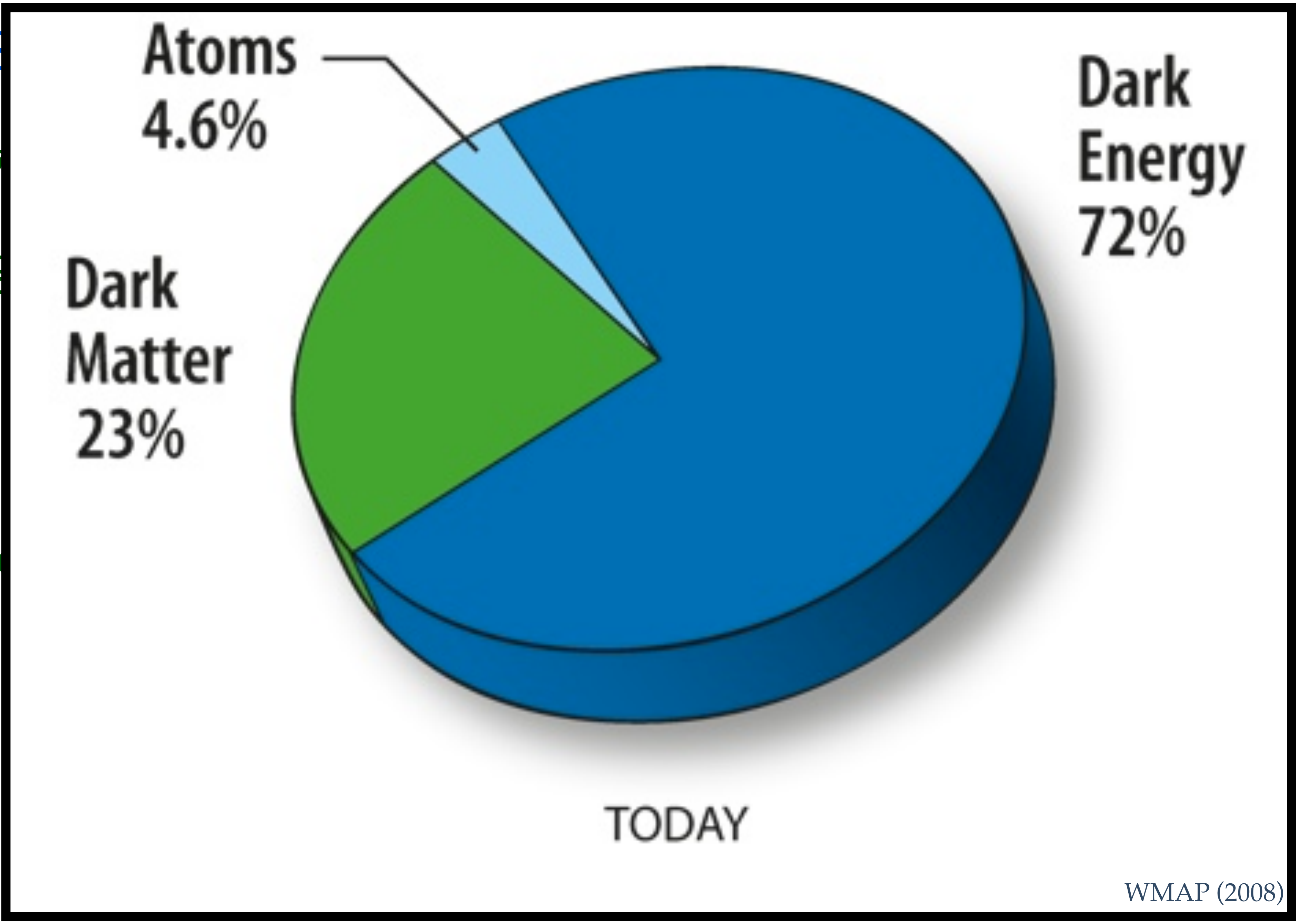

WMAP (2008)

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The Theory [Deshpande, Ma '78; Ma '06; Barbieri, Hall, Rychkov '06]

- **a 2 Scalar Doublets: H_1, H_2**
- **with unbroken Z_2 symmetry: H_2 is odd, SM particles even**

Most general scalar potential:
[Z_2 symmetry: $H_2 \to -H_2$]

$$V = \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \lambda_5 Re\left[(H_1^\dagger H_2)^2\right]$$

'Inert doublet': H_2 has no vev, nor couplings to SM fermions

Vacuum exp. value "SM Higgs boson"

$$H_1 = \begin{pmatrix} 0 \\ v + h/\sqrt{2} \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H^\pm \\ (H^0 + iA^0)/\sqrt{2} \end{pmatrix}$$

Inert scalar doublet Inert scalars

$$m_h^2 = -\mu_1^2 \equiv 4\lambda_1 v^2$$
$$m_{H^\pm}^2 = \mu_2^2 + \lambda_3 v^2$$
$$m_{A^0}^2 = \mu_2^2 + \lambda_A v^2 \qquad (\lambda_A = \lambda_3 + \lambda_4 - \lambda_5)$$
$$m_{H^0}^2 = \mu_2^2 + \lambda_L v^2 \qquad (\lambda_L = \lambda_3 + \lambda_4 + \lambda_5)$$

6 free parameters

[*e.g.*: the 4 masses, λ_L, and the self coupling λ_2]

Constraints I

Theoretical:

- Vacuum stability:

$$\lambda_{1,2} > 0, \quad \lambda_3, \lambda_3 + \lambda_4 - |\lambda_5| > -2\sqrt{\lambda_1 \lambda_2}$$

- Perturbative:

$$\lambda_3^2 + (\lambda_3 + \lambda_4)^2 + \lambda_5^2 < 12\lambda_1^2, \quad \lambda_2 < 1. \qquad \text{or} \quad \lambda_i \lesssim [1, 4\pi]$$

- By construction: No CP violation, nor tree-level FCNC

Colliders, LEP I+II:

- Z,W mass-widths (~~$W \to H^\pm H^0, H^\pm A^0$~~ ; ~~$Z \to H^0 A^0, H^\pm H^\mp$~~) $\begin{cases} m_{H^\pm} + m_{H^0, A^0} \gtrsim m_W \\ m_{H^0} + m_{A^0}, 2m_{H^\pm} \gtrsim m_Z \end{cases}$

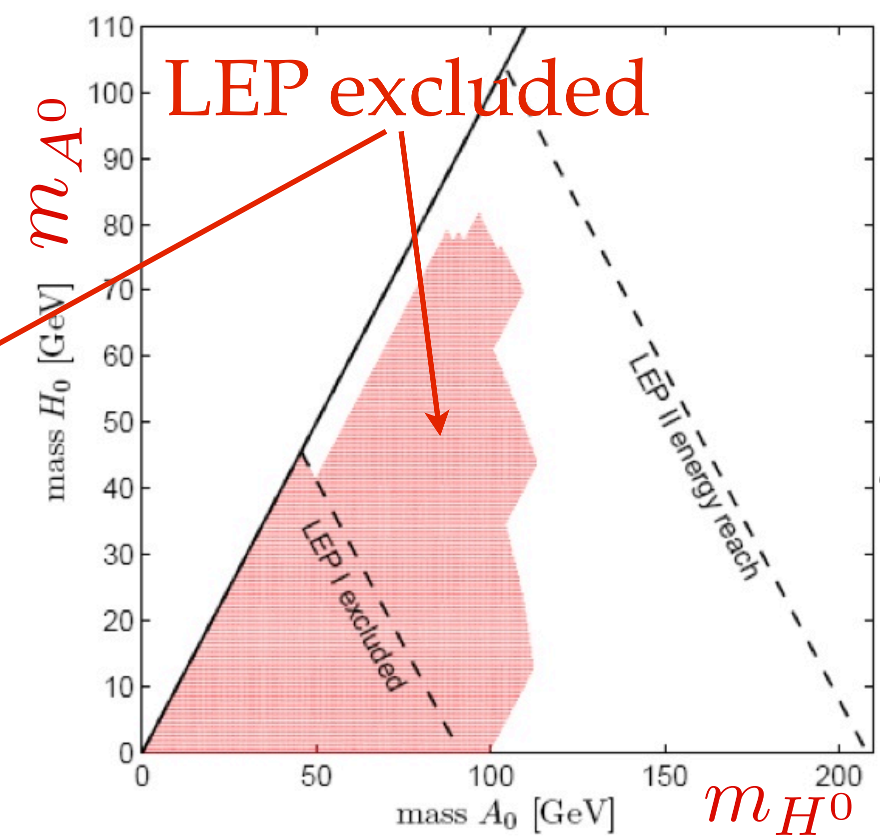
- From SuSy searches $\Rightarrow$

$$m_{H^\pm} \gtrsim 70 - 90\,\text{GeV}$$ (within IDM?)

<u>Excludes</u> IDMs with:

$$m_{H^0} \lesssim 80\,\text{GeV}, \; m_{A^0} \lesssim 100\,\text{GeV}$$

$$\text{and} \quad \Delta m_{A^0 - H^0} \gtrsim 8\,\text{GeV}$$



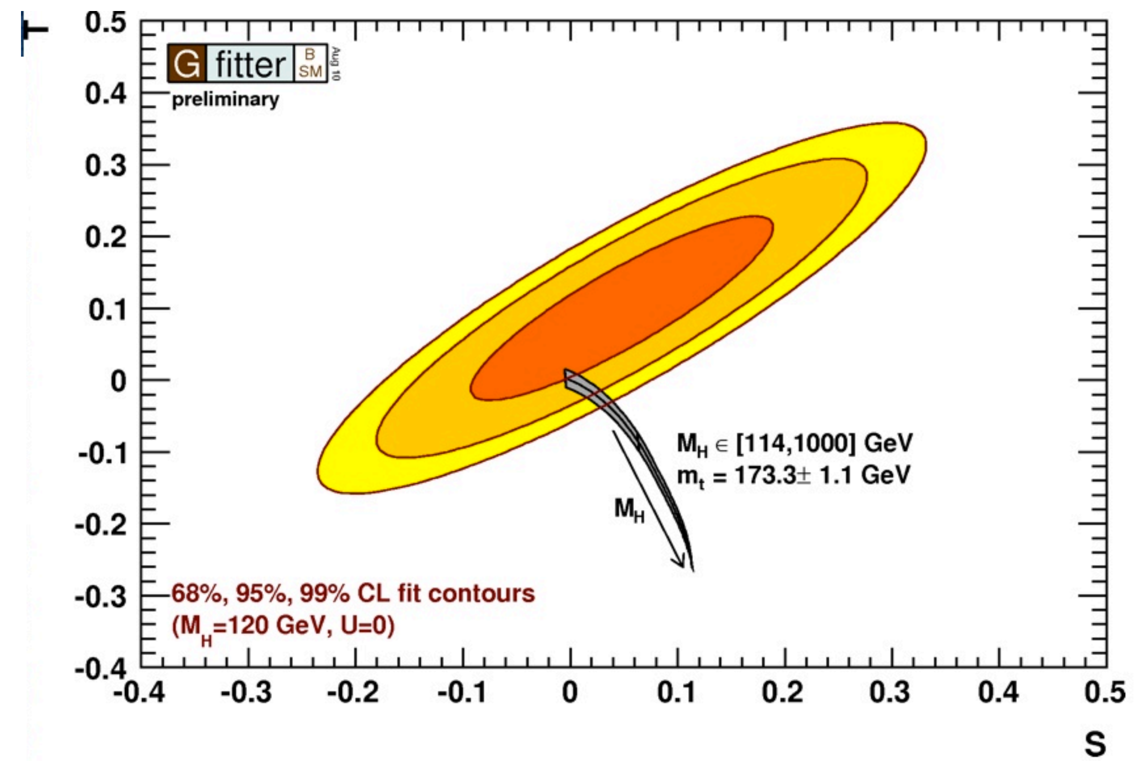
Lundstöm, MG, Edsjö, 2009

Constraints II

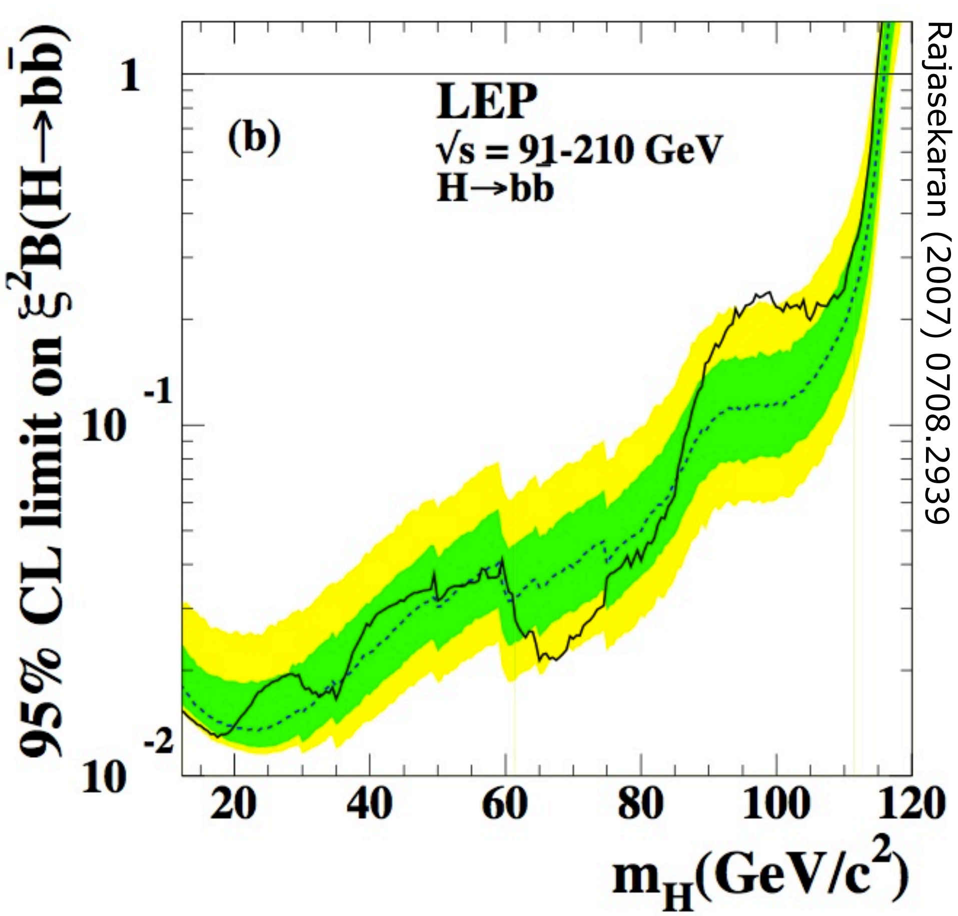
ElectroWeak precision tests (EWPT):

if low 'SM' higgs mass -> check no IDM contributions enters
if high 'SM' higgs mass -> check IDM loop contributions compensate to achieve agreement with EWPT

E.g. m_h= 500 GeV $\Rightarrow$ $(M_{H^+} - M_A)(M_{H^+} - M_H) = M^2, \;\; M = 120^{+20}_{-30}\text{GeV}$



Direct Higgs searches:



LEP Higgs Working Group (2001); Cao, Ma and Rajasekaran (2007) 0708.2939

$$BR(inv) \equiv \frac{\Gamma(h_{SM} \to H^0H^0)}{\Gamma(h_{SM} \to b\bar{b}) + \Gamma(h_{SM} \to H^0H^0) + \Gamma(h_{SM} \to A^0A^0)} < BR_{max}(inv)$$

$$BR(b\bar{b}) \equiv \frac{\Gamma(h_{SM} \to b\bar{b})}{\Gamma(h_{SM} \to b\bar{b}) + \Gamma(h_{SM} \to H^0H^0) + \Gamma(h_{SM} \to A^0A^0)} < BR_{max}(b\bar{b})$$

IDM as the Dark Matter I

Z_2-parity ⟶ Lightest Inert Particle (LIP) is perfectly stable

If H^0 or A^0 is the LIP
↓
WIMP dark matter candidate!

For simplicity: choose H^0 as the LIP...

Thermal production:

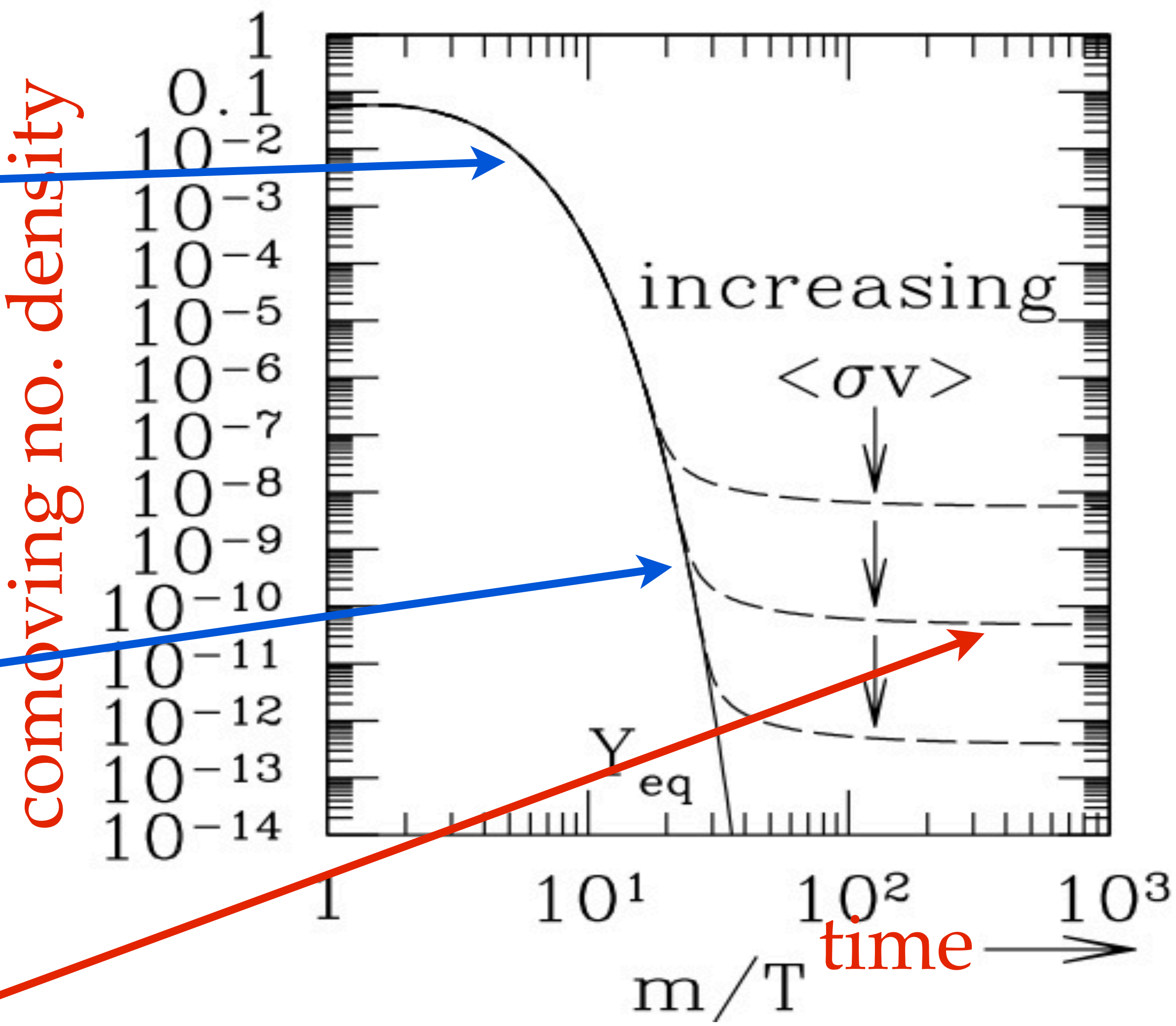
$$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle \sigma v \rangle \left[n_\chi^2 - n_{\chi,\mathrm{eq}}^2 \right]$$

$$\Gamma = \langle \sigma v \rangle n_\chi >> H$$

↓

$$n_\chi \to n_{\chi,\mathrm{eq}}$$

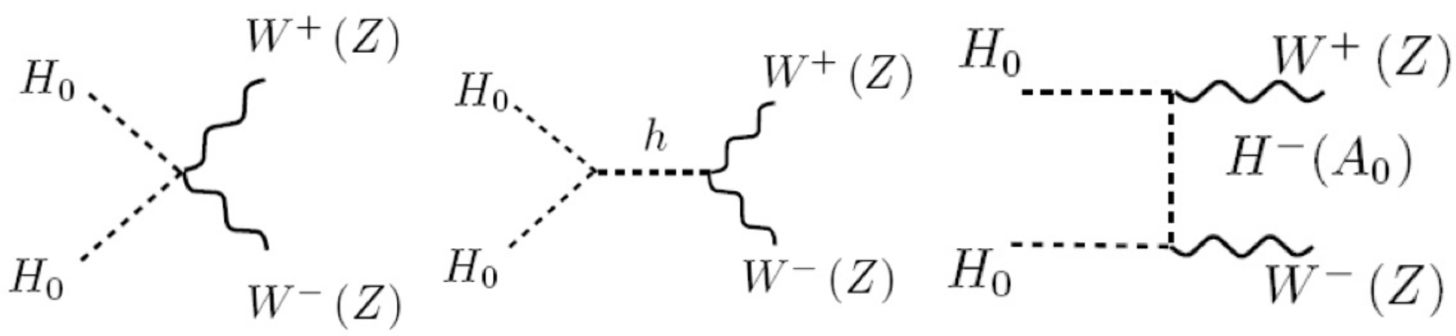
$H \sim \Gamma$: "Freezeout"



$$\Omega_{CDM} \approx \frac{6 \times 10^{-27}\,\mathrm{cm}^3/\mathrm{s}}{< \sigma v >} \approx 0.23\%$$

IDM as the Dark Matter II

Annihilations into gauge bosons (strong):

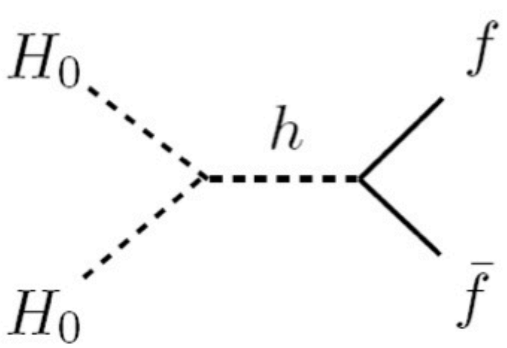


(+ 3 body final state implications. [Honorez, Yaguna, 1003.3125])

If kinematically accessible
↓
Relic density typically too low to explain all dark matter...

(Also a ~**TeV mass DM region**)

Annihilations into fermions (weak):



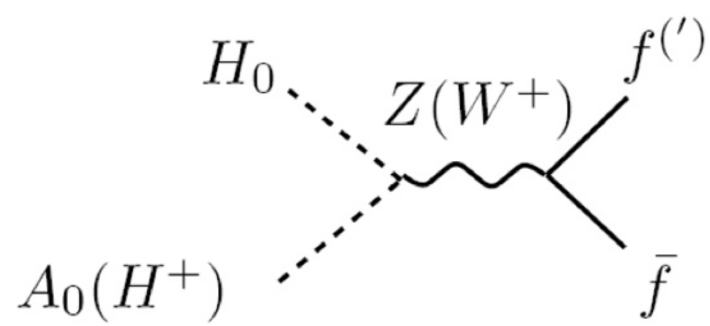
Amplitude ~ $\frac{\lambda_L}{m_h^2}$

If heavy ~500 GeV

Relic density typically too high...

(Also a **~10-80 GeV mass** DM region if light ~120 GeV SM Higgs)

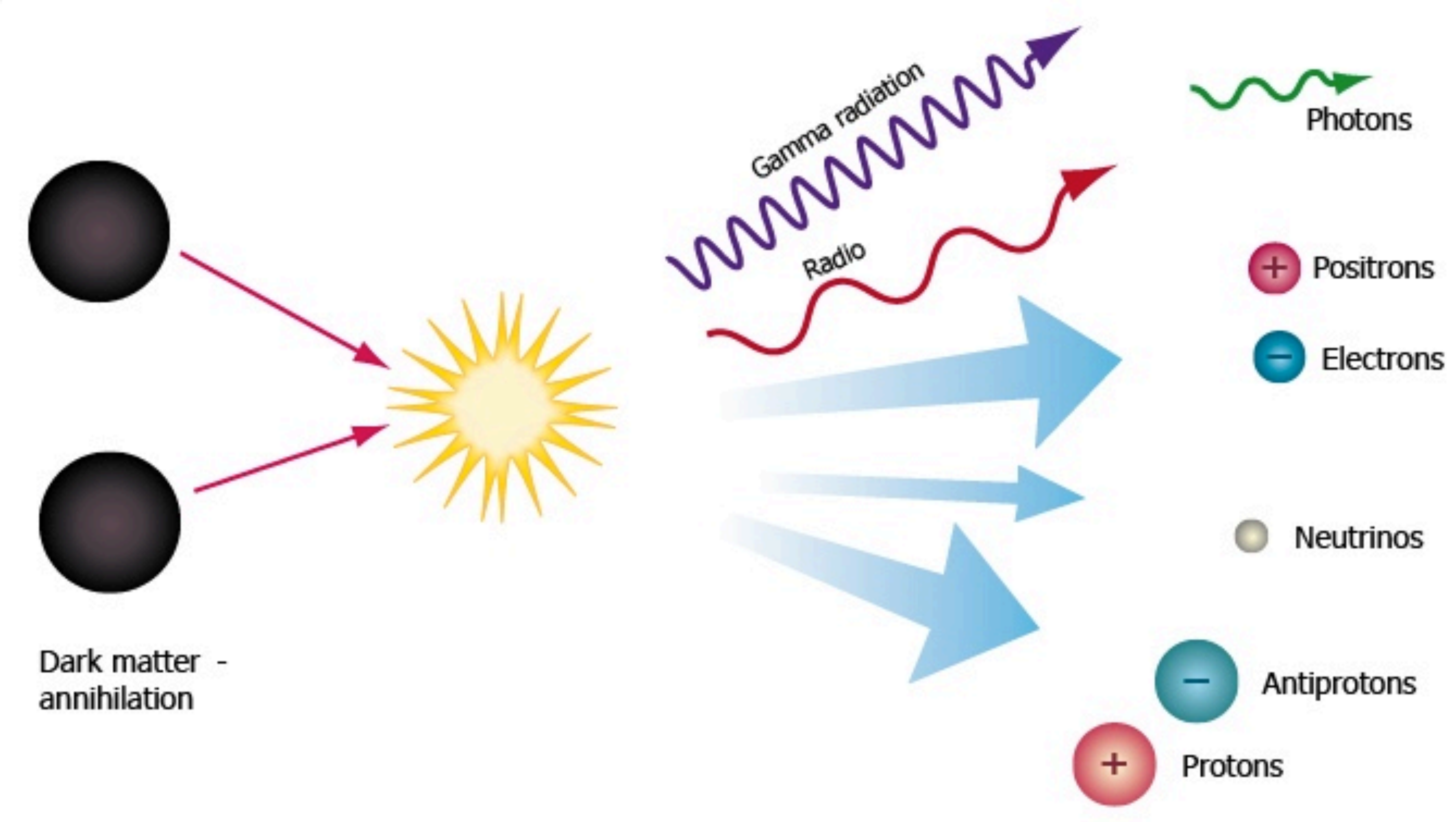
Coannihilations into fermions:



Coannihilations can lower the relic density!

A LIP lighter than ~80 GeV can provide all the dark matter

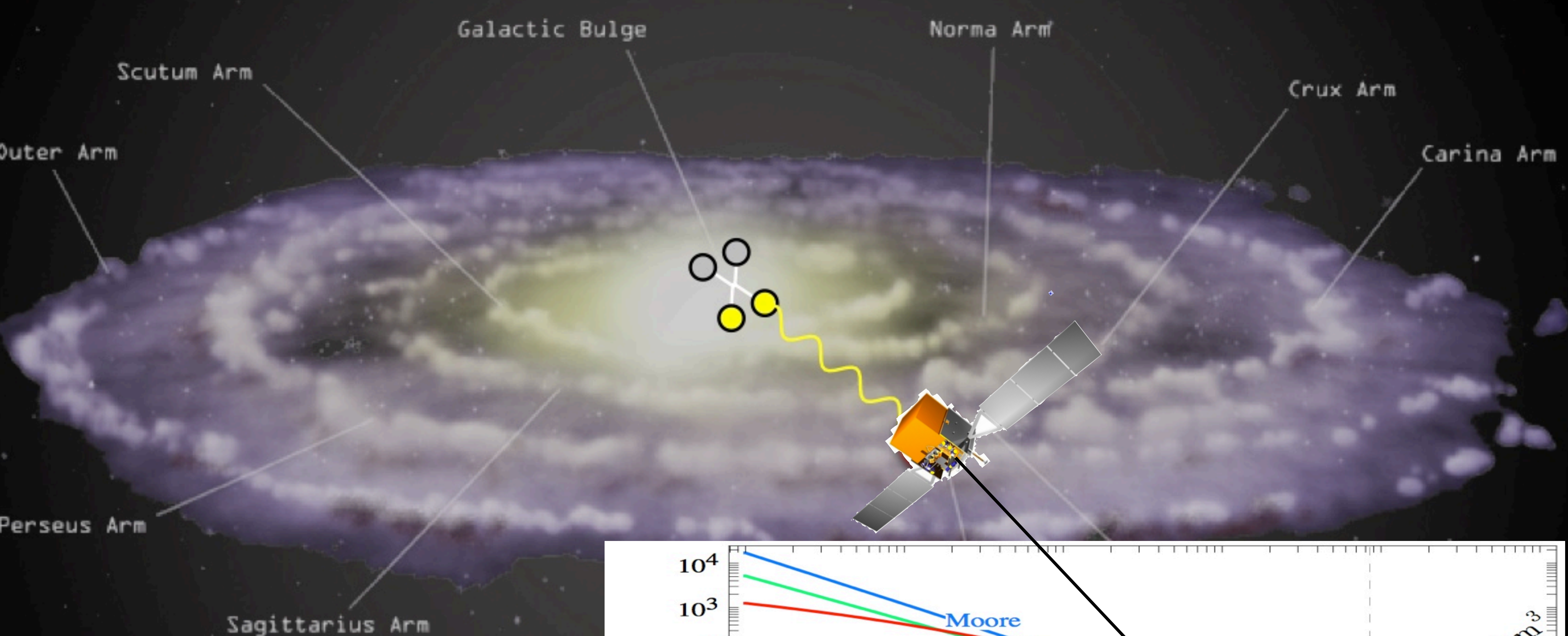
Indirect Dark Matter Detection

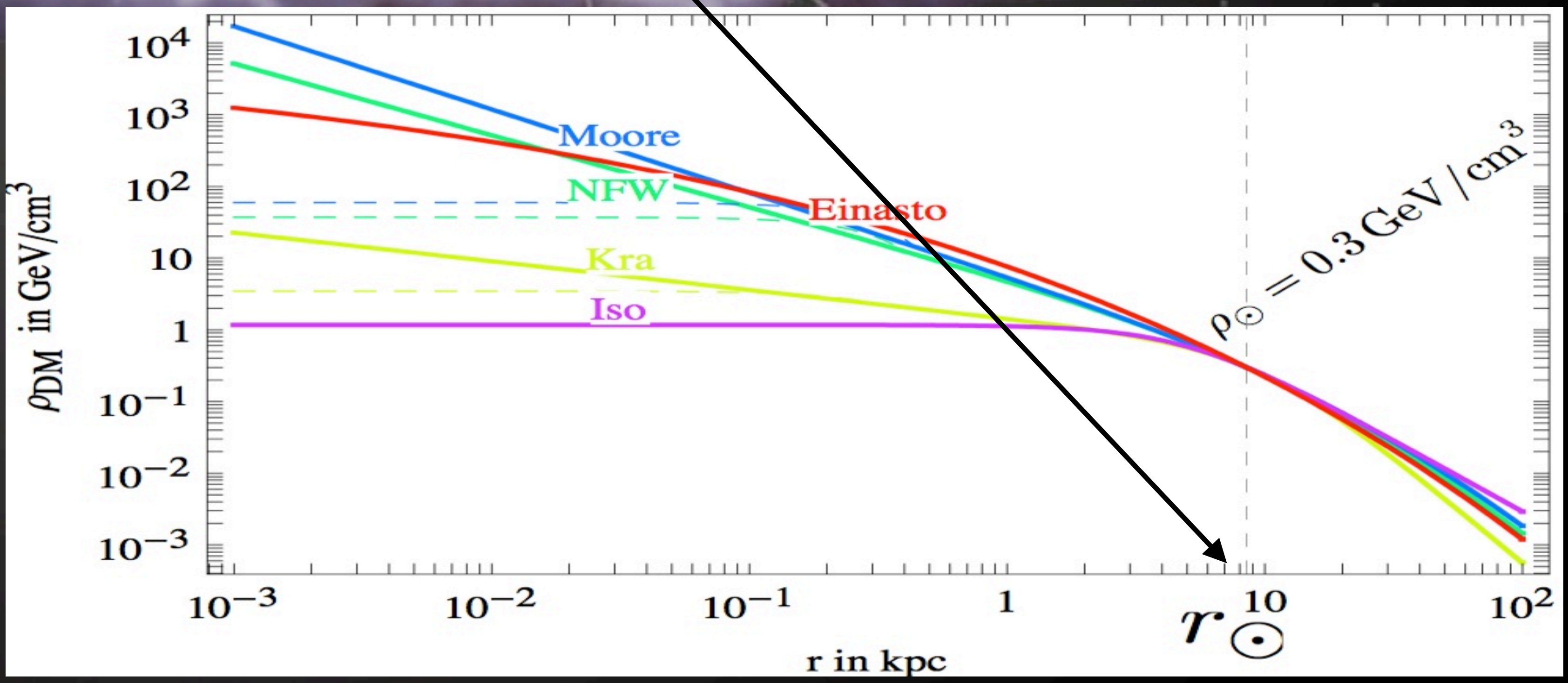


Dark matter particles annihilate

.... and inject an energy $E = 2\ m_{DM}c^2$ into SM particles

Gamma-rays from Dark Matter



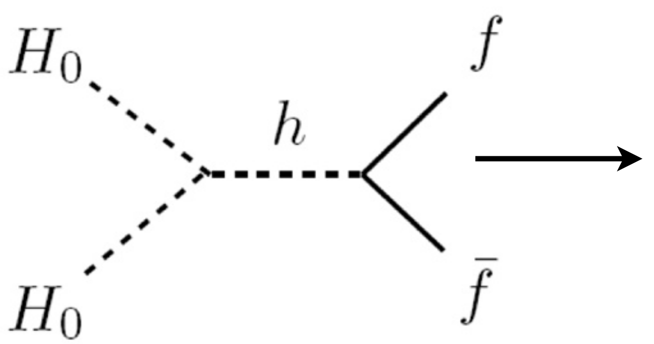


Dark matter embed our Galxy. DM density profile →

Fig courtesy: Marco Cirelli

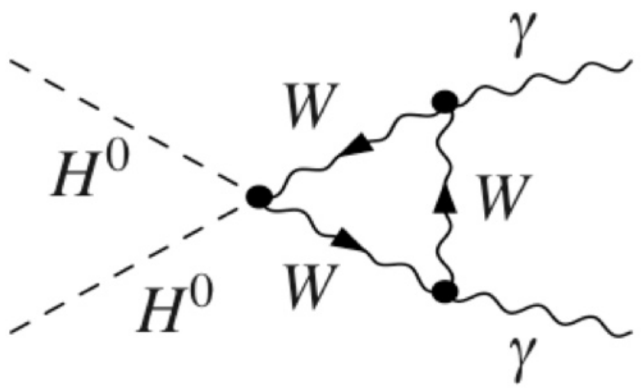
IDM gamma-ray signal

In the IDM the continuum spectrum is suppressed:



Hadronization $\rightarrow \pi^0$ decays

Whereas loop processes can give strong lines:



Monochromatic gamma-rays

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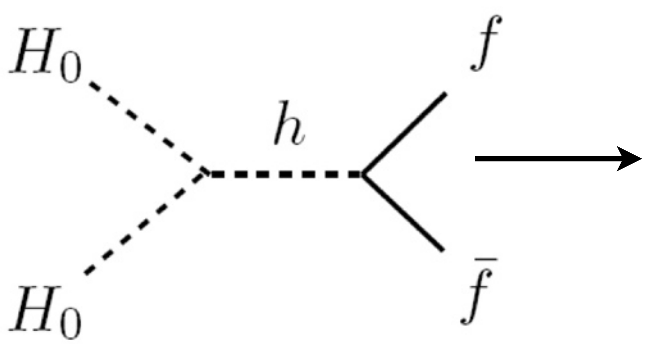

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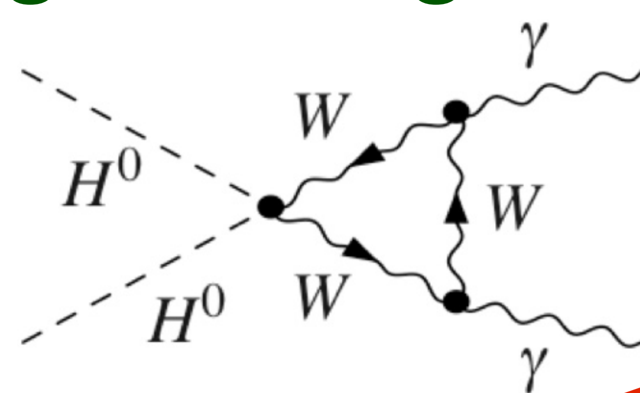

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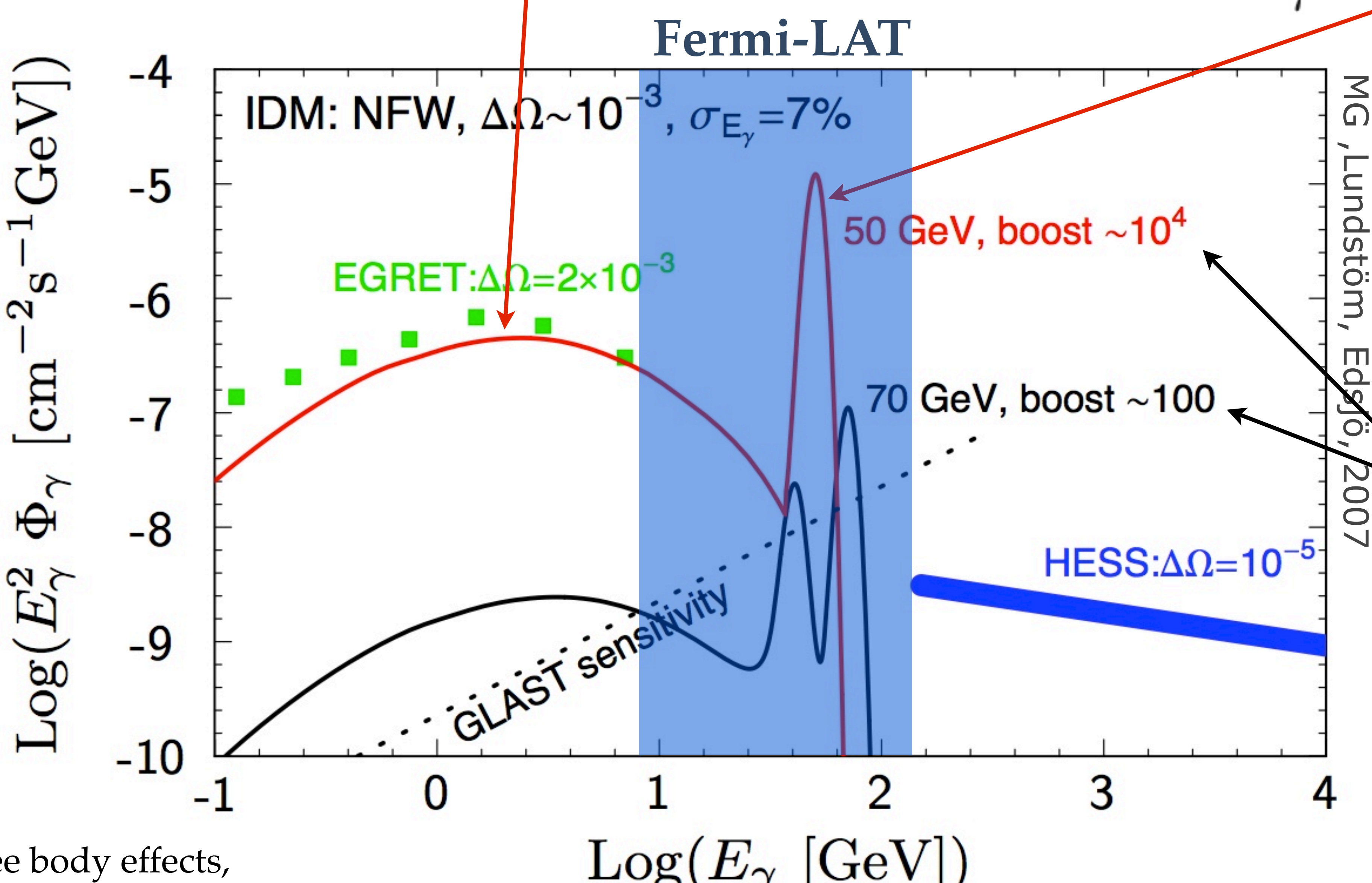


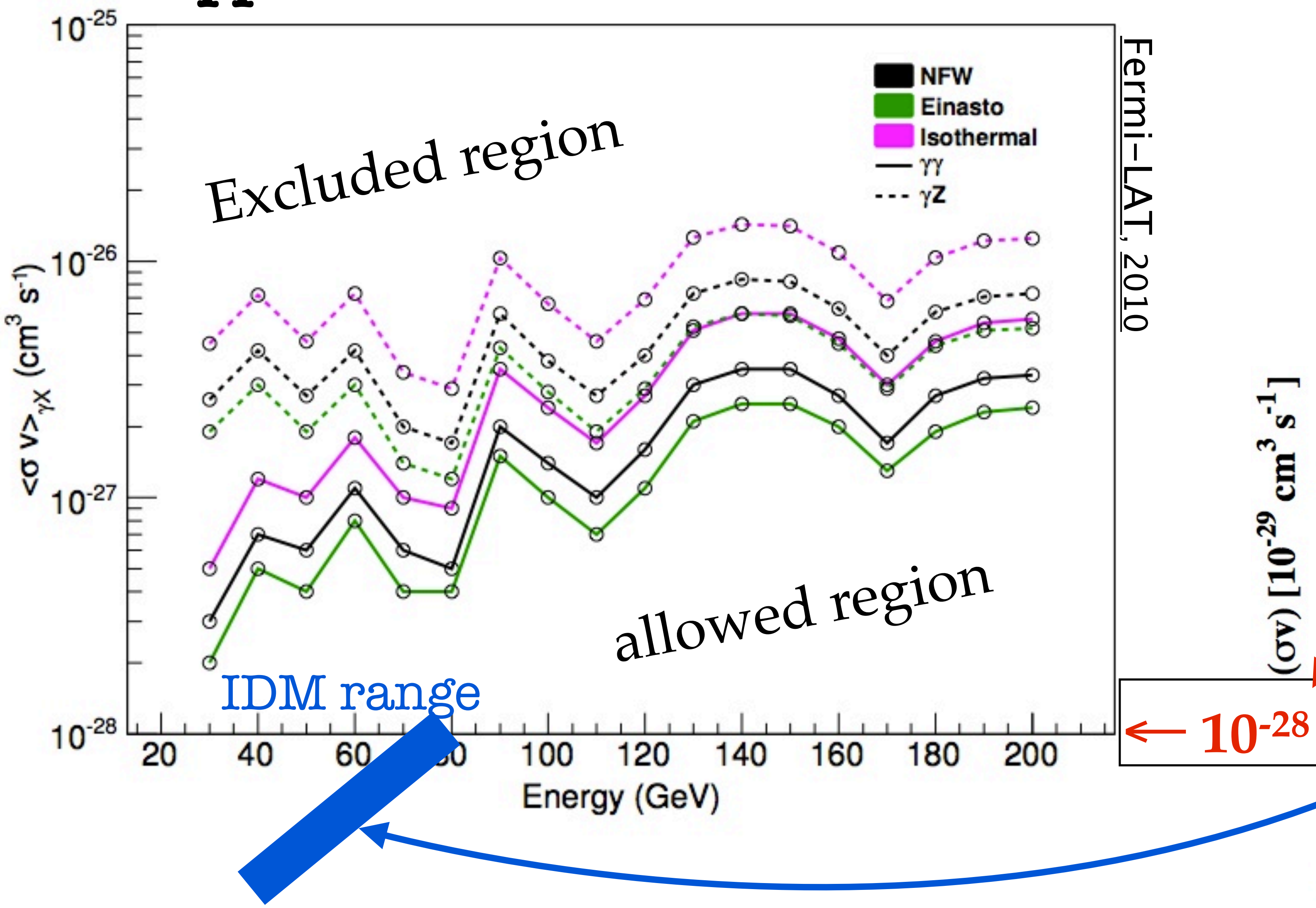
Speculative boosts due to Black Hole effects in the Galactic center

N.B. Three body effects, work in progress

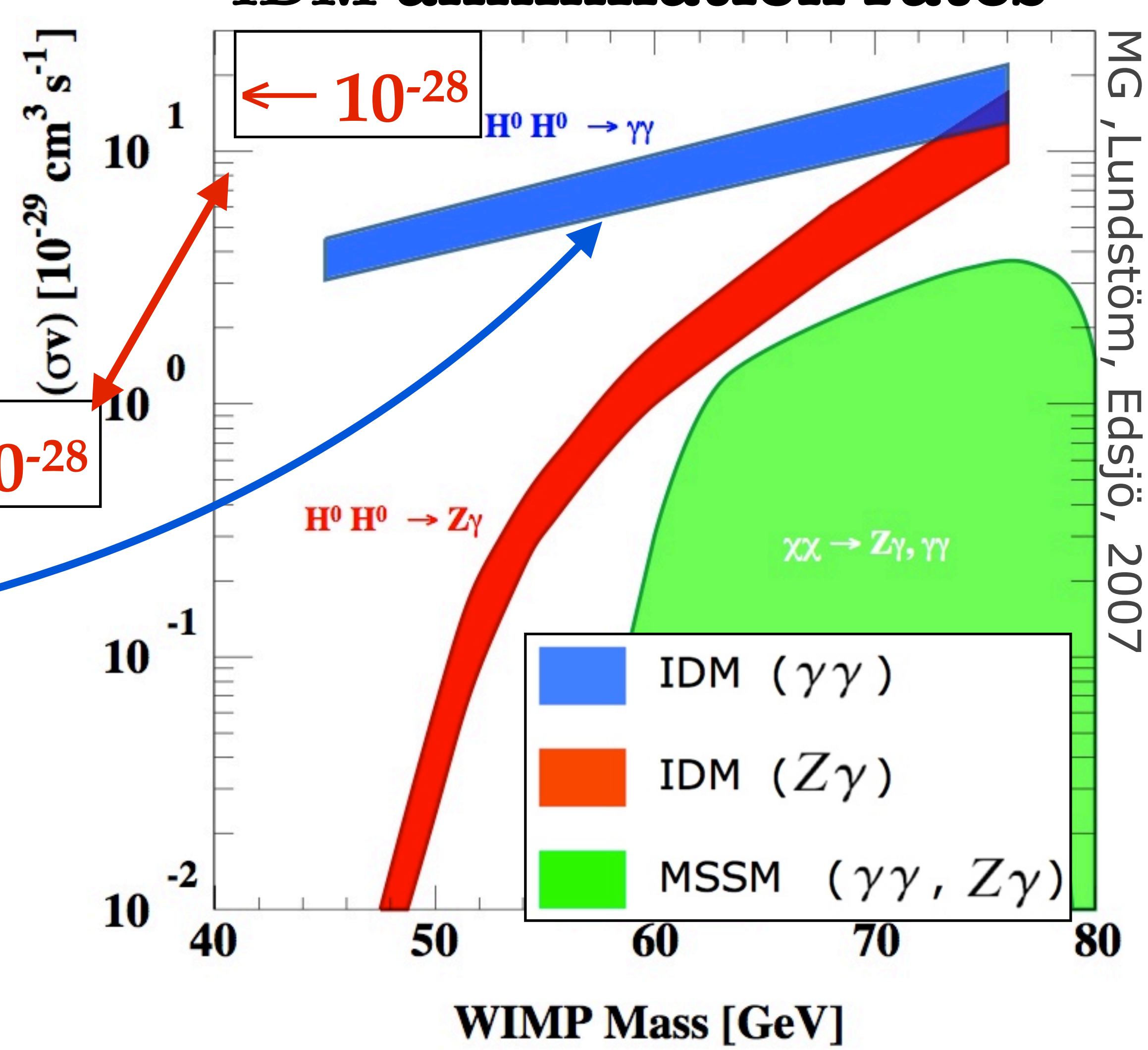
IDM confronting Fermi-LAT data:

No monochromatic line yet detected by Fermi-LAT (1 year):

Upper limits: annihilation rates



IDM **annihilation rates**



⇒ **IDM gamma-lines allowed, but not with large boosts**

Neutrinos

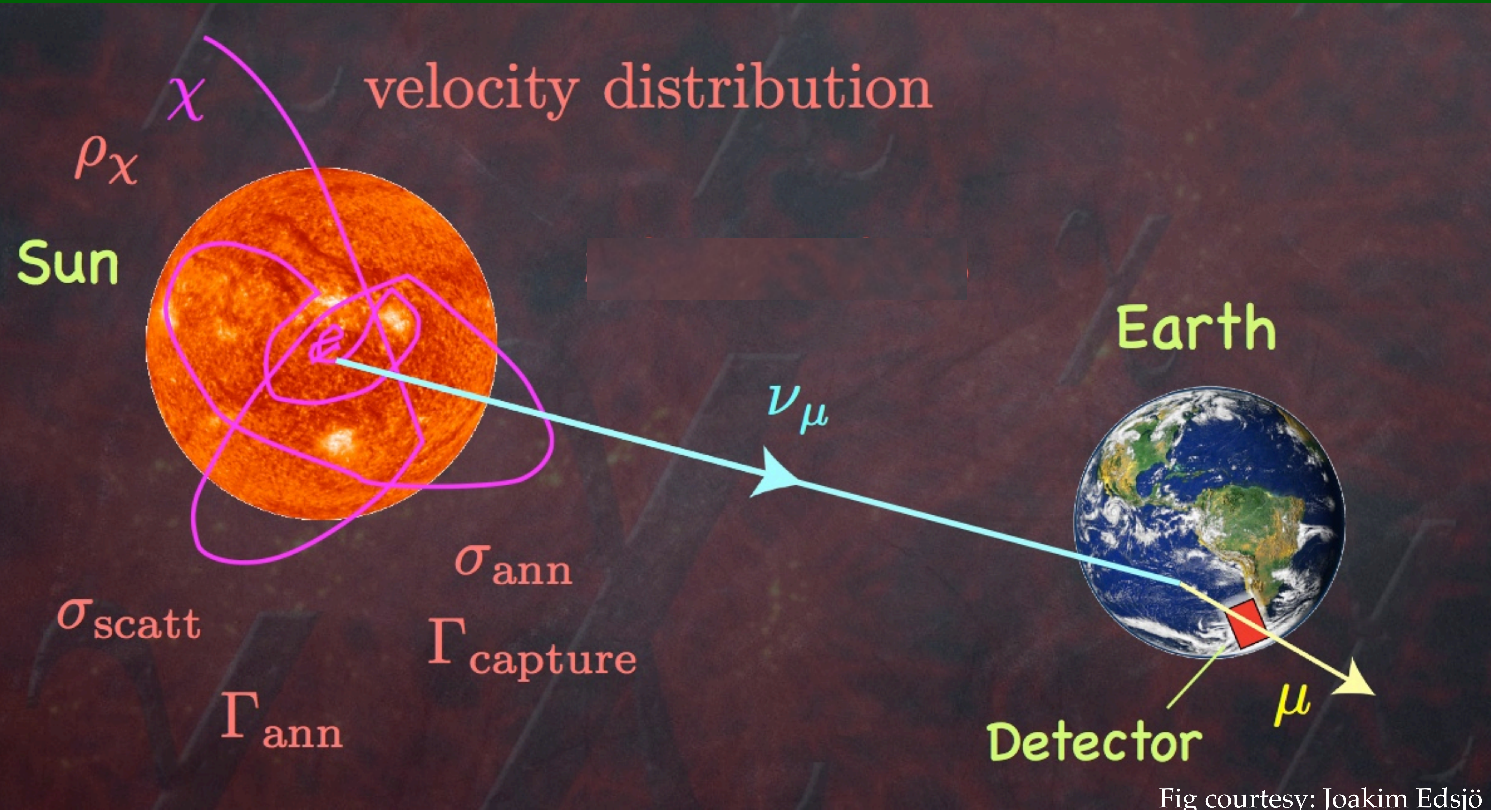


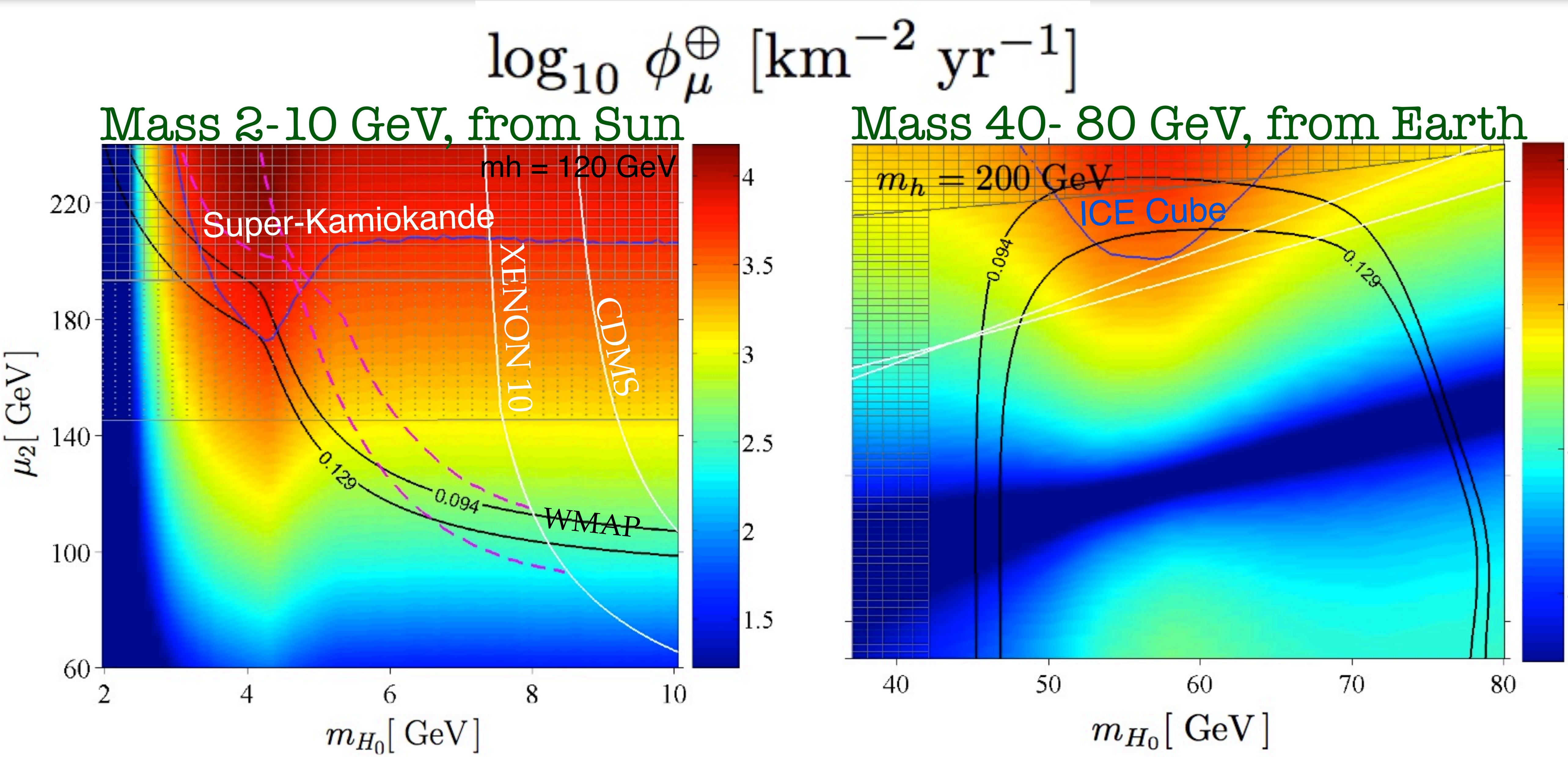
Fig courtesy: Joakim Edsjö

H^0 capture in the Sun (or Earth)

→ **annihilations ' into' neutrinos**

→ **detection of neutrino induced muons**

Confronting IDM with neutrino data



Andreas,Tytgatt Swillens 2009 [0911.0540]

Parameters:
$\lambda_2 = 1$ (dotted) and $\lambda_2 = \pi$ (shaded)

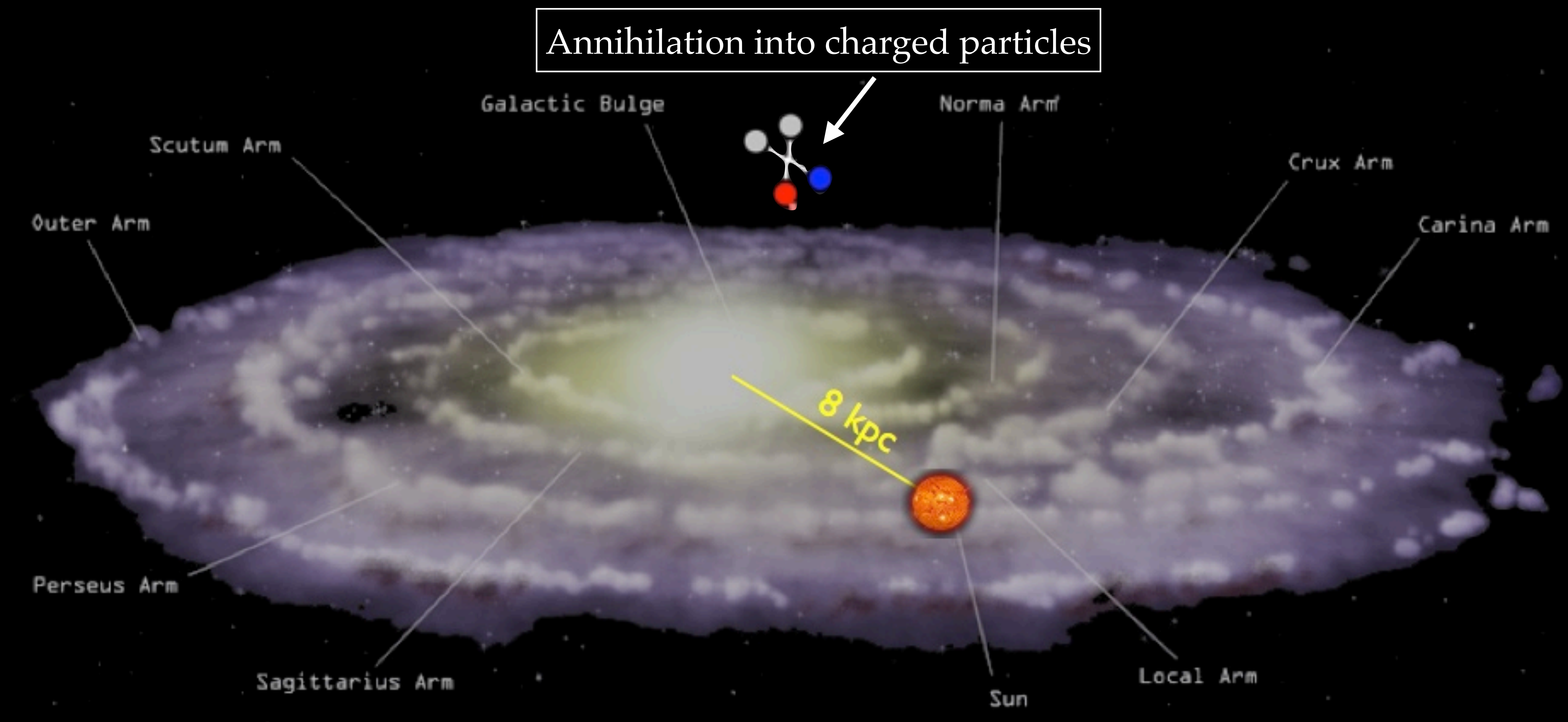
Parameters:
$\lambda_2 = 0.2$, $\Delta m_{AH} = 8$ GeV, $\Delta m_{H+H} = 50$ GeV

IDM not very constrained by neutrino data

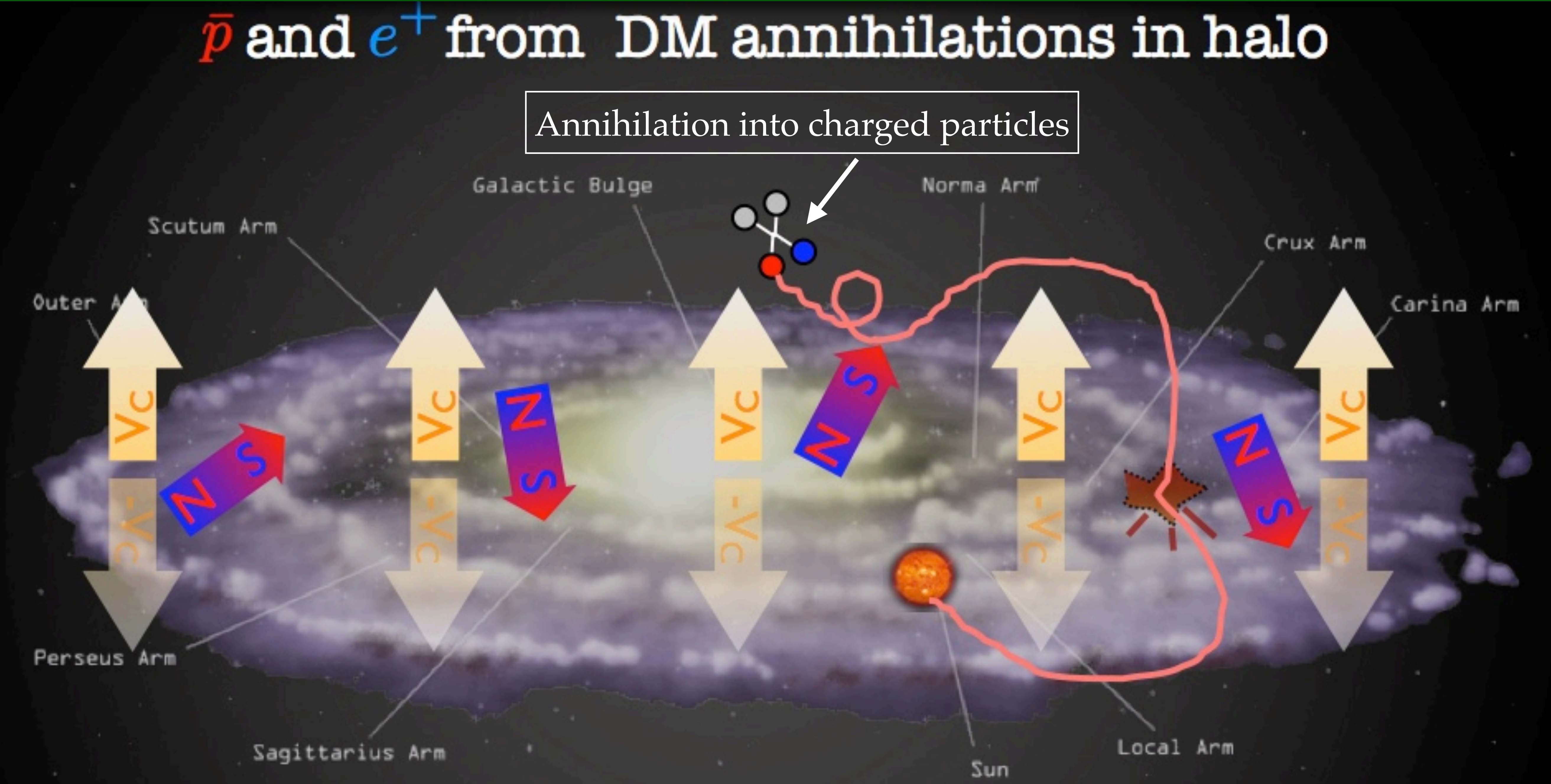
See also Agrawal, Dolle, Krenke, 2009 [0811.1798]

Antiprotons and positrons

$\bar{p}$ and e^{+} from DM annihilations in halo

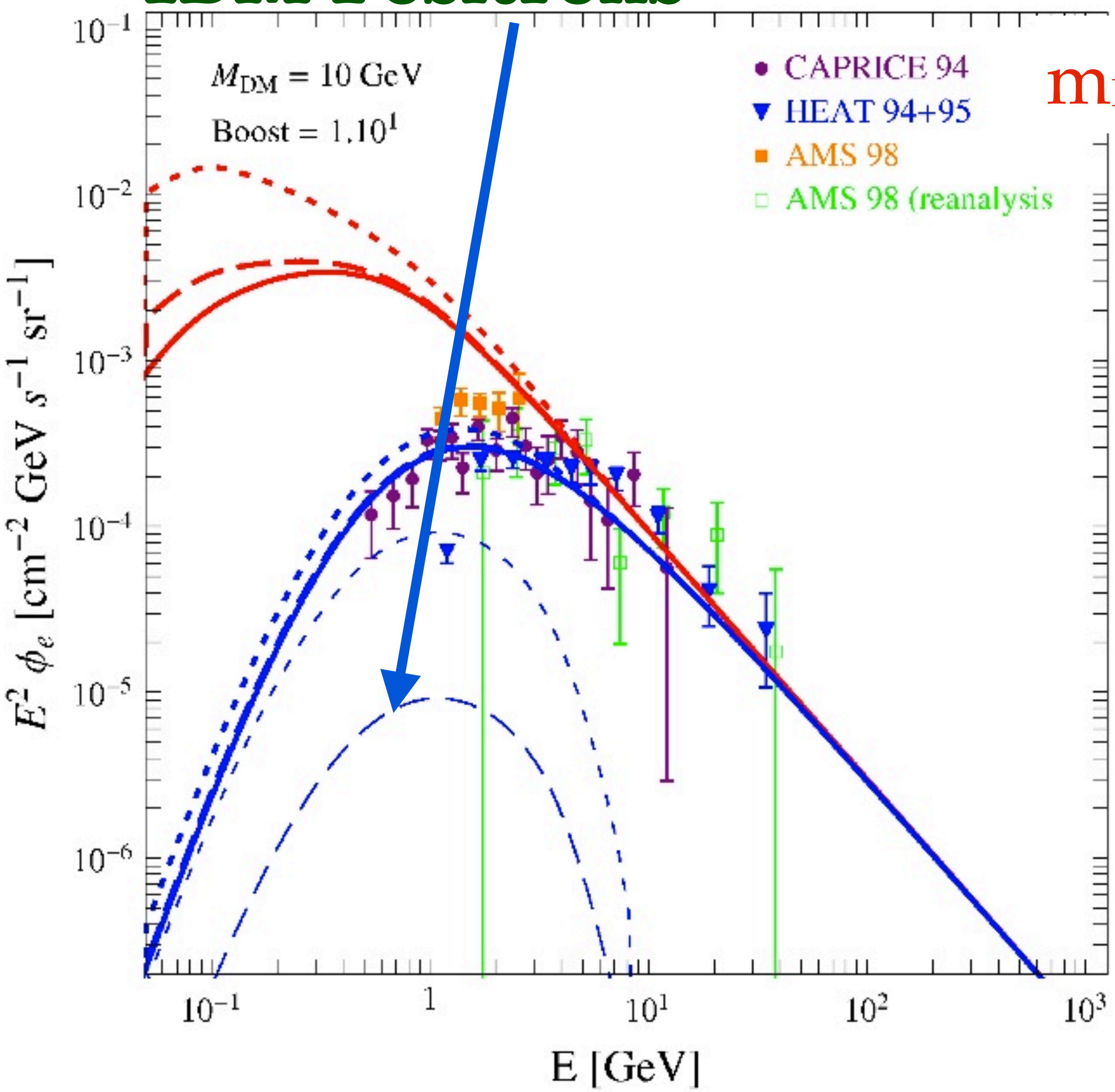


Antiprotons and positrons



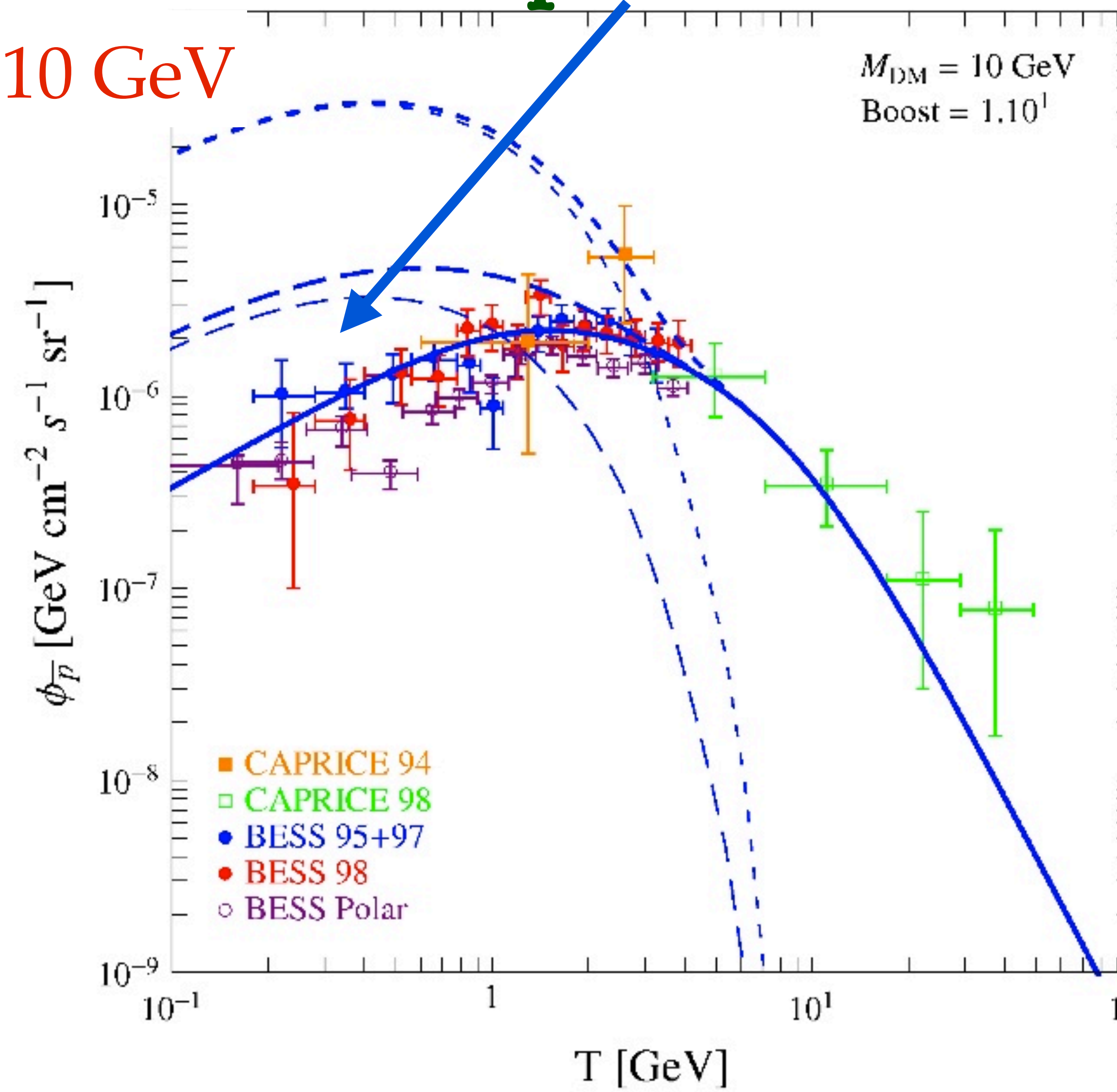
Positrons and anti-protons

IDM Positrons



IDM Antiprotons

m_{H0}= 10 GeV



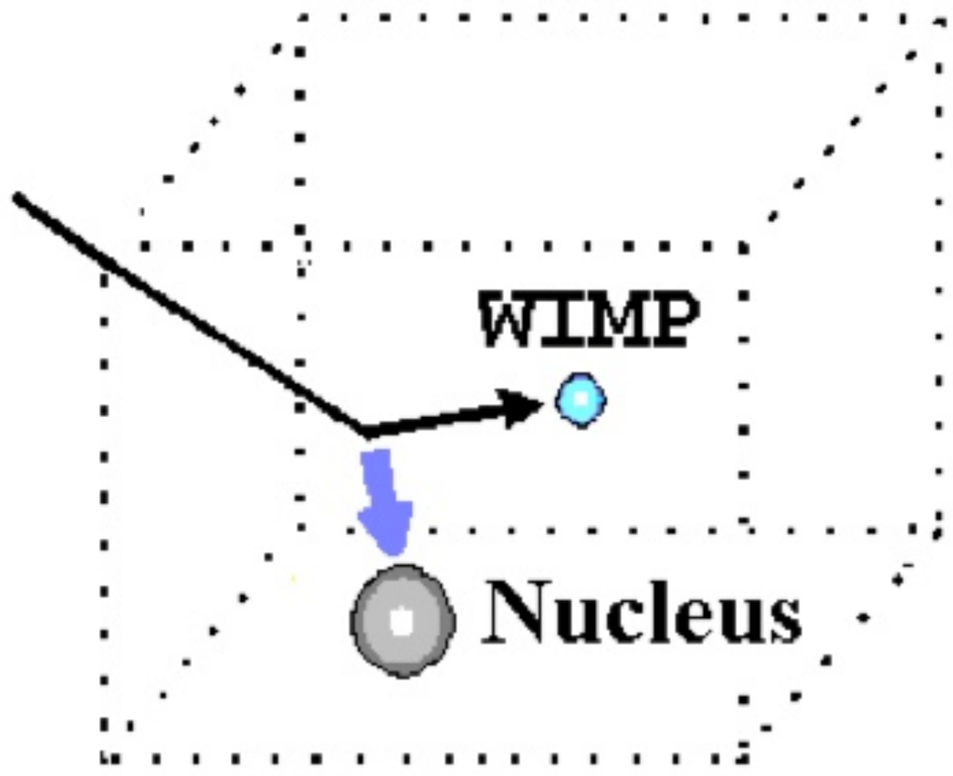
Nezri, Tygat and Vertonge (2009)

Weak positron signal

'Strong' antiproton signal for < 10 GeV DM, but propagation uncertainties…

Direct Detection searches

Dark matter particles elastically scatter...

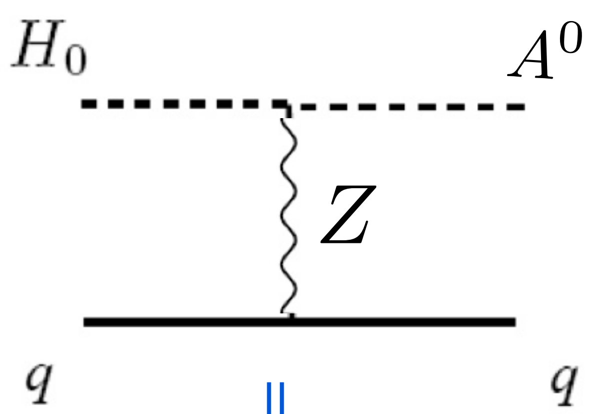


... off a nuclues

Low background (deep underground) detector

searching for the recoil energy

Direct Detection:



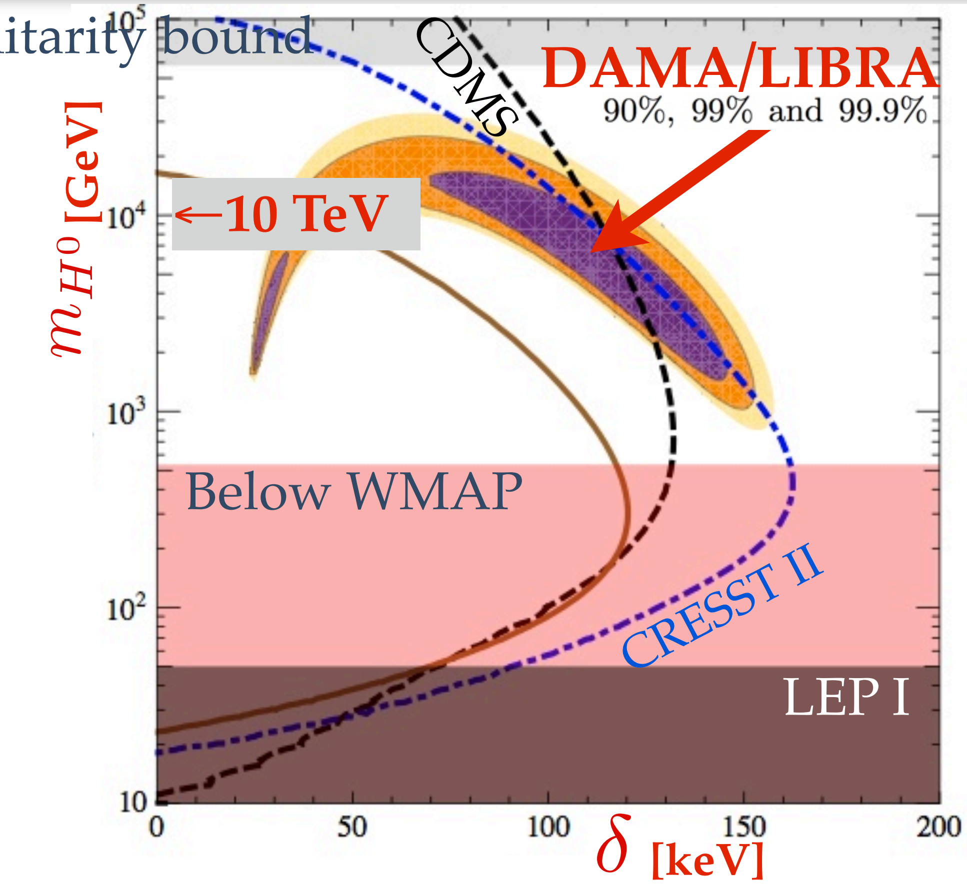
$\Downarrow$

Give too strong couplings $\Rightarrow$

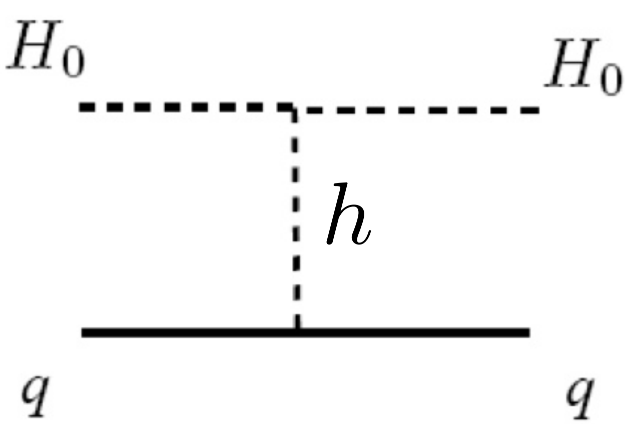
$$\delta = m_{A^0} - m_{H^0} \gtrsim 100\,\text{keV}$$

$\Rightarrow$ OR? $\Rightarrow$

~ Peccei-Quinn symmetry



Arina, Ling, Tytgat, 2009



$\Downarrow$

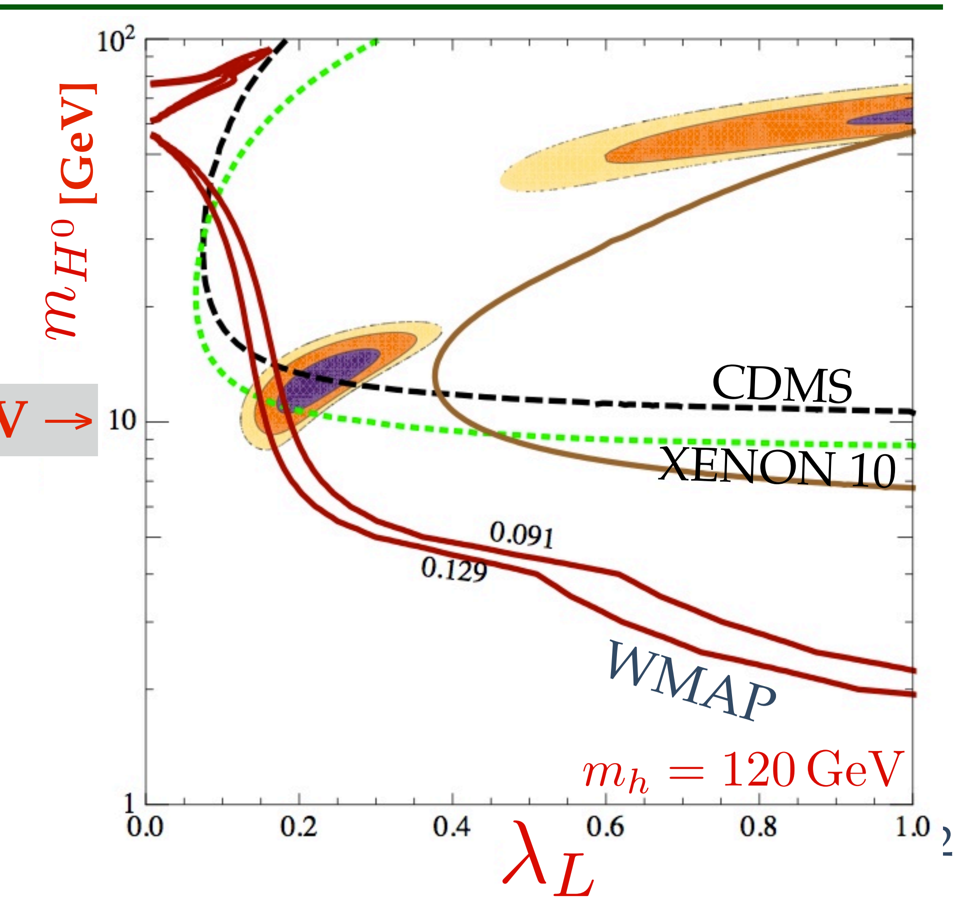
$$\sigma = \frac{1}{4\pi}\left(\frac{m_r m_N}{m_S}\right)^2 \left(\frac{\lambda_L f}{m_h^2}\right)^2$$

$\Rightarrow$ OR? $\Rightarrow$

$M_{H_0} \ll M_{A_0} \approx M_{H^\pm}$

$\Rightarrow$ Bounds on couplings vs masses

10 GeV $\rightarrow$



Summary

The Inert Doublet Model:

- a phenomenological rich model despite its simplicity

- Provides a good dark matter candidate with reachable astrophysical signals:

  - Striking gamma-ray line
  - Direct detection prospects
  - Antiprotons, neutrinos, positrons signals?

- No conclusive detection of beyond SM particles:
  - Limits on the IDM's parameters
  - Still room for interesting signals and upcoming astrophysical detections